High efficiency microwave and millimeter-wave electro-optical modulation with whispering-gallery resonators

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ABSTRACT

We present electro-optic modulator based on toroidal lithium niobate cavity with whispering-gallery modes, superimposed with stripline resonator. With microwave resonance (quality-factor $Q \sim 10^2$) tuned to the free spectral range of optical modes ($Q \sim 5\times10^6$), controlling power $\leq$10mW is achieved in 9GHz prototype, and preliminary results with 33GHz prototype are obtained. Further efficiency improvement will enable various applications in microwave photonics.

Keywords: Microsphere, microcavity, photonics, electrooptic modulator

1. INTRODUCTION

Microspherical resonators supporting optical whispering gallery (WG) modes have attracted considerable attention in various fields of research and technology. Combination of very high Q-factor (typically 10^6-10^9 depending on the material) and small physical dimensions makes these resonators attractive new components for a number of applications, including basic physics research, molecular spectroscopy, narrow-linewidth lasers, optoelectronic oscillators (OEO), and sensors [1-4]. Effective methods of coupling light in and out of WG modes in microspheres are currently being developed, including single mode fiber couplers and integrated waveguides [5,6]. Whispering-gallery resonators made of nonlinear optic material can be suggested as a basis of efficient resonance electro-optic modulator [7].

Motivation for optical cavity-based modulator stems from the large operating power required to drive the existing modulators. Both broadband integrated Mach-Zender modulators and free space RF cavity-assisted narrow-band modulators require about one Watt of RF power to achieve significant modulation index. By utilizing, as a principle for electro-optic modulation, high-Q resonance instead of zero-order interferometry or polarization rotation, one can potentially reduce the controlling power by many orders of magnitude, at the expense of limited bandwidth that is acceptable for number of applications. Whispering-gallery modes, in addition, combine high Q with very small cross section of annular optical field localization, similar to that of integrated waveguides. As a result, RF can be applied to a small dielectric gap (increasing the field at a given voltage) and yet a small capacity load so that a high Q microwave cavity can be easily built around. The core of the device can be a sphere made out of second-order nonlinearity material, such as lithium niobate.

Optical losses in lithium niobate are sufficiently low to allow relatively high Q-factor of whispering-gallery modes, and small voltage applied across the area of optical field localization is enough to provide displacement of WG resonance curve comparable to its bandwidth – a basis of efficient modulation. For high-speed modulation, at radio frequencies exceeding the optical resonance bandwidth, the frequency of applied electrical field has to coincide with the separation between adjacent whispering-gallery modes.

We have designed, fabricated and tested a prototype of such an electro-optic modulator in the X-band (at 9GHz), and also present preliminary data on the prototype working in the Ka-band (at 33GHz).

2. OPTICAL RESONATORS OF LITHIUM NIOBATE

High-Q whispering-gallery modes have been studied extensively in fluid droplets and solid glass microspheres, both produced by surface tension forces in liquid phase. The resulting surface quality (inhomogeneities in the sub-nanometer

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range) allows for very low scattering losses, so that quality-factors approaching 10^{10} have been demonstrated with high-purity silica as material [8]. With crystalline materials, fusion method is not applicable, and spheres with adequate surface quality have to be obtained with grinding and polishing techniques. However, because of higher intrinsic optical attenuation compared to silica, residual surface roughness requirements are relaxed [9] so that the quality-factor up to 1×10^7 in mechanically polished spheres can be expected without major efforts.

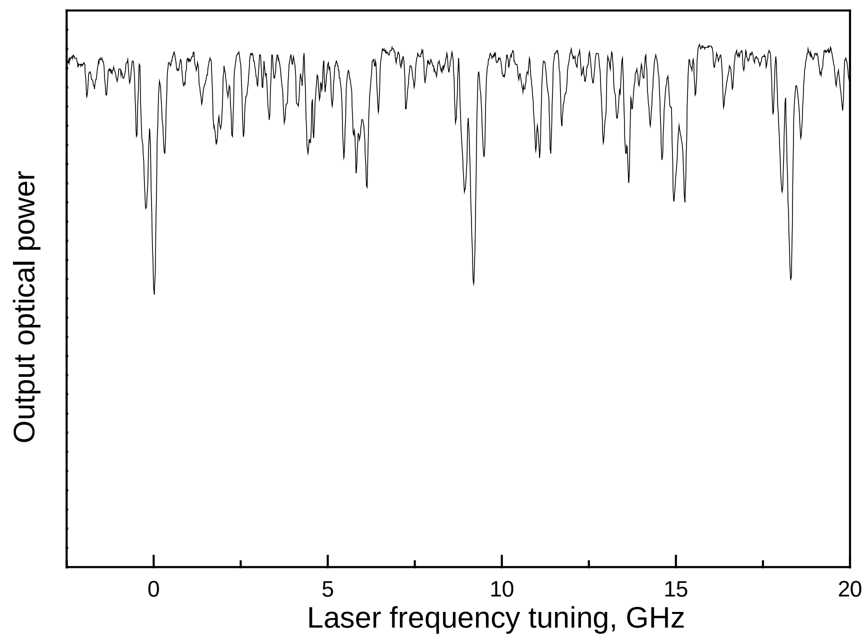

Fig.1. Optical spectrum of TE whispering-gallery modes in equatorial layer of lithium niobate sphere, diameter 4.8 mm. Optical Q = 2×10^6; free spectral range 9.2 GHz

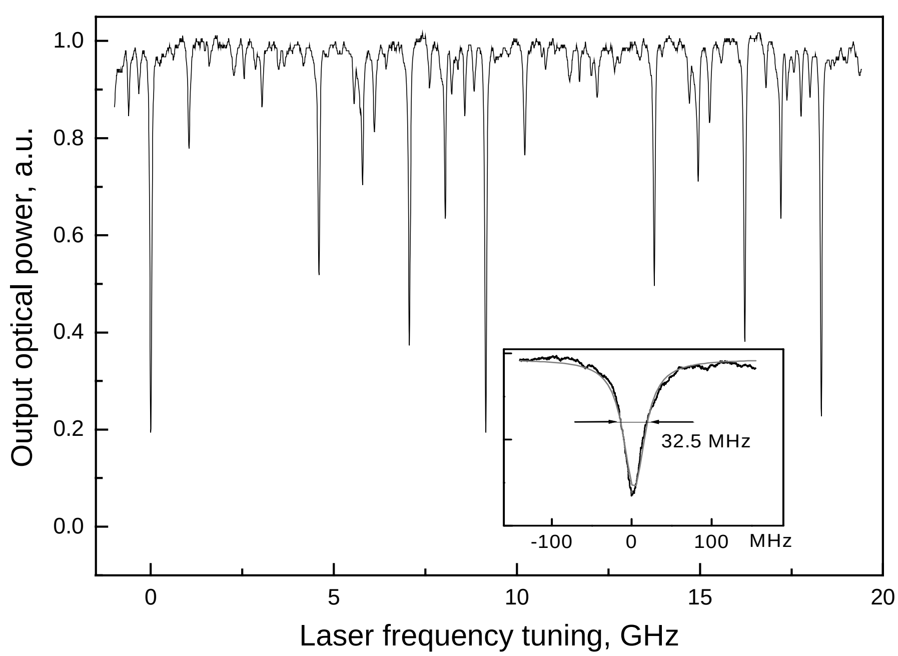

Fig.2. Optical spectrum of TE whispering-gallery modes in toroidal (oblate spheroidal) lithium niobate resonator; diameter 4.8mm, thickness 150mm; transverse curvature diameter 180mm. Optical Q=6.3×10^6, FSR 9.155GHz.

Fig.1 presents the optical spectrum of TE-type whispering-gallery modes in the equatorial layer of 4.8mm diameter sphere that we used in one of our initial prototype modulators. The layer was cut perpendicular to the crystal axis within tolerance of less than 0.2^{o}. The spectrum was obtained with single coupler prism and two fiber collimators. Structure of the spectrum reveals quasi-periodicity with the “large” optical free spectral range near the microwave frequency 9.16GHz, consistent with the inverted round-trip time of light along the circumference of the sphere. Identification of detailed mode structure is complicated because 1)modelling of WG modes in anisotropic sphere is very complicated theoretically, 2)addressing particular modes requires precise tailoring of launching angles beyond capabilities of our setup. Nevertheless, spectrum was in qualitative agreement in terms of basic free spectral range, and also optical quality-factor $Q \sim 2\times10^{6}$ estimated from individual peaks, was suitable for preliminary modulation experiments.

Fig.2 presents the optical spectrum (TE) of the improved optical cavity that we prepared out of commercial flat Z-cut $LiNbO_3$ substrate. Diameter of the resonator was 4.8mm, thickness 150 micron, and transverse curvature diameter 180mkm. Improved polishing procedure results in higher $Q = 6.3 \times10^{6}$; and the novel toroidal geometry [10] – in much cleaner mode structure with distinct individual resonance peaks. Contrast of absorption peaks, observed in fiber-to fiber transmission upon scanning of the driving tunable DFB laser, is more than 80%. Free spectral range is 9.155GHz. Typical optical power in our mesurements was 2 to 5mW at the wavelength 1550nm.

3. MICROWAVE MODULATION

Cavity-based modulator requires that the input laser radiation be tuned in frequency to a particular mode, while modulation sidebands will result from the nonlinear-optic excitation of adjacent Stokes and anti-Stokes modes. Because subsequent WG modes differ in their azimuthal field dependence by exactly one period added to closed circular waves, the microwave field applied to the resonator may not be uniform along the rim, otherwise nonlinear polarization will not have azimuthal

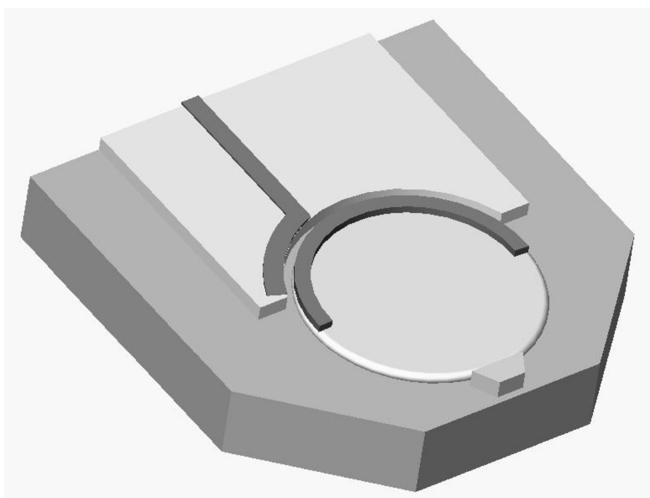

Fig.3. Schematic of the modulator based on toroidal lithium niobate cavity. Resonator is placed on common metal base with the driving RF coupler and the optical coupling prism. Half-wave microstrip cavity is arranged by deposition of metal electrode over the rim of optical resonator; RF cavity is trimmed to frequency match the optical FSR

frequency corresponding to adjacent modes. To taylor the RF field structure for optimal nonlinear-optic interaction, we used half-wave microstrip cavity arranged by placing a half-circular electrode along the rim of the resonator (Fig.3). Typical Q-factor of such an RF cavity is 100-150, bandwidth 60-100MHz, close enough to the bandwidth of optical resonances. By trimming the length of the stripline electrodes microwave cavity can be tuned to the frequency equal the optical FSR.

Presented in Fig.4 is the typical frequency response of the modulator: with laser constantly kept at resonance with one of WG modes, we scanned the microwave frequency and recorded the demodulated RF power produced by high-speed photodetector at the end of output optical fiber. Three-dB bandwidth of the modulator is consistent with bandwidthes of optical and microwave cavities. The two curves presented are taken well under saturation limit represented by zero dB level in Fig.4; smallest detectable RF power (sensitivity of photonic reciever) was about 1 nanoWatt.

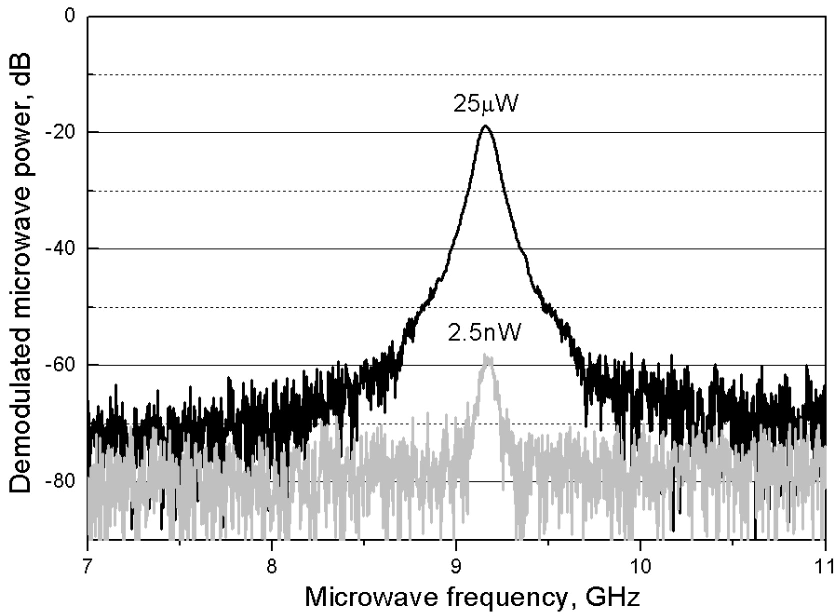

Fig.4. Frequency response of the microwave modulation in X-band prototype.
Zero dB level corresponds to full saturation and occurrence of strong harmonics

Presented in Fig.5 is the saturation curve, i.e. the RF power response of the modulator. Turnover point at ~11mW corresponds to the limit imposed by harmonic multiplication; optimal operational power within linear regime can roughly be estimated as 1mW.

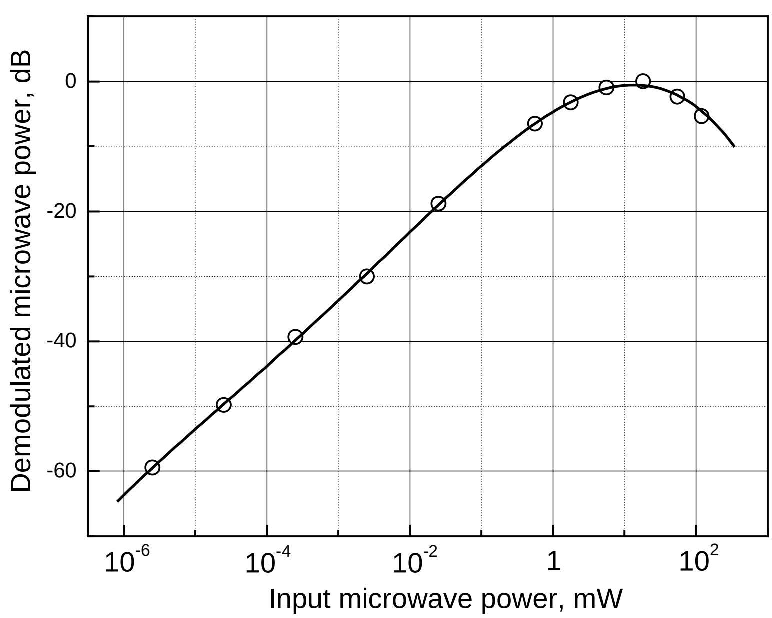

Fig.5. Microwave power response (saturation curve) of the X-band prototype.

Finally, Fig.6 presents the preliminary experimental data for the Ka band modulator prototype. Toroidal optical resonator has diameter 1.35mm, thickness of 120micron and transverse curvature diameter 150micron. Optical free spectral range is 33.1GHz; quality-factor ~1×10^6, partially due to the full contact prism coupler. Microwave cavity quality-factor 60. Because of the significantly smaller Q-factors, despite smaller dimensions and mode volumes, we were not able to reach saturation

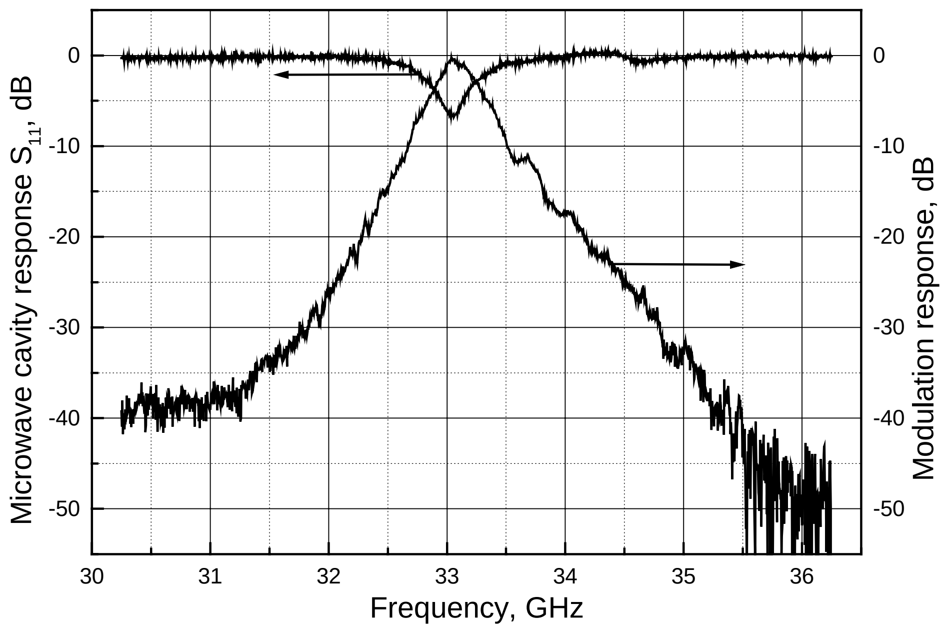

Fig.6. Frequency response of the microwave modulation in preliminary Ka-band prototype.
Input microwave power 20mW. Zero dB level is arbitrary

with available maximum RF power of ~30mW in these initial experiments. Improvement of surface quality in these small mechanically polished resonators, introduction of prism-resonator airgap to optimize coupling strength, and elimination of extra losses in RF cavity will result in reduction of required controlling RF power in our future prototypes.

This description is a report of technical achievements; detailed description and complete theoretical analysis of the new modulator will be published elsewhere [11].

4. CONCLUSION

We demonstrate experimentally a novel configuration that allows us to take advantage of high-Q whispering gallery modes excited in a nonlinear dielectric resonator to create efficient mixing of light and microwave fields. We overcome restrictions normally imposed on similar interactions by phase-matching conditions via engineering the doubly resonant optical and microwave resonator. With the idea in hand we devise optical modulator with small controlling power ~1mW and photonic microwave receiver with nanoWatt sensitivity.

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